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**TOR STUBB · RALF GRAEFFE**

## A Study of the quantum efficiency of X-ray radiation absorbed in a p—n junction

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CONTENTS

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An earlier work [1] which was concerned with efficiency in a p-n junction has given rise to a more detailed study of similar problems whereas the emphasis in previous work has been laid on the measurement of physical magnitudes of units, such as the lifetime of charge carriers, the diffusion length, and quantum efficiency. Measurements have been made on specially made diodes. Tauc dealt with a similar problem starting from other assumptions [2] .

We used X-rays, as these seemed to give complementary possibilities in the problems dealt with here, though without eliminating the difficulties which arise through the thermal behaviour which is generally observed.

In contrast to Tauc, the charge carrier lifetime has been measured by a pulse method, as mentioned by Lederhandler [3] . A control measurement of this value has also been made by irradiating the unit with Co-60. The results from both methods were in agreement.

## The sensitivity of the photodiode

The photo element consisted of germanium with a p-n junction near the irradiated area, see Fig. 1. The site of the irradiated area was called A, and the p-layer thickness d. The thickness of the n-layer must be large in comparison with the depth of radiation.

If the increase caused by irradiation in the speed of generation of p-n pairs is g, and the radiation penetration depth is $L_\lambda = 1/\mu$ then one can write from well-accepted theory:

$$g(x) = \frac{\eta I_0}{Eg\, L_\lambda} e^{-(d+x)/L_\lambda} \qquad (1)$$

$\eta$ efficiency
$I_o$ the incident radiation intensity expressed in energyflow per unit area
$E_g$ the energy of the forbidden energy gap

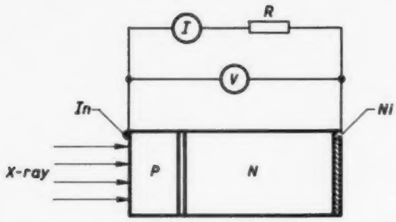



Fig. 1

The shortcircuit current of the element consists of that part of the generated minority carriers which reaches the p-n junction through diffusion. If $L_n$ and $L_p$ denote diffusion lengths for electrons in p-type material and holes in n-type material respectively, we have, according to [2] , for the shortcircuit current:

$$I_k = A\ e \left\{ \int_{-d}^{o} g\,(x)\ e^{\frac{x}{L_n}}\, dx - \int_{o}^{\infty} g\,(x)\ e^{\frac{-x}{L_p}}\, dx \right\} \qquad (2)$$

By substitution of the value of g ( x ) according to ( 1 ) and integrating, we have

$$I_k = \frac{A e\ I_o \eta}{Eg} \left\{ \frac{e^{\frac{d}{L_\lambda}}}{L_\lambda} \left[ \frac{L_n}{\frac{L_n}{L_p} - 1} \left( e^{\left(\frac{1}{L_\lambda} - \frac{1}{L_n}\right) d} - 1 \right) + \frac{L_p}{\frac{L_p}{L_\lambda} - 1} \right] \right\} \qquad (3)$$

From now on, the expression within brackets { } will be termed $f_1$. By using a slightly different method, [ 1] and [4] , we have for the shortcircuit current

$$I = \frac{Ae\ I_o \eta}{E_g} \left\{ \frac{e^{\frac{d}{-L_\lambda}}}{L_\lambda} \left[ \frac{L_p}{\frac{L}{L_\lambda} - 1} + \frac{L_n}{\left(\frac{L_p}{L_\lambda}\right)^2 - 1} \left( \frac{L_n\, e^{\frac{d}{L_\lambda}}}{L_\lambda \cosh \frac{d}{L_n}} - \frac{L_n}{L_p} - \operatorname{tgh} \frac{d}{L_n} \right) \right] \right\} \qquad (4)$$

This expression within brackets { } will be termed $f_2$ . Both equations show that the shortcircuit current is linearly dependent of the radiation intensity $I_o$ , the area

A, and the energy which is used to generate one electron-hole pair $E_g / \eta$. On the other hand, it is more difficult directly to indicate the influence that the parameters in the function $f_1$ have on the shortcircuit current.

While $\eta i$ is the efficiency, indicating how large a part of the absorbed energy is used to generate electron-hole pairs in semiconductor material, so can $f_1$ be considered as showing how much of the generated charge carriers contributes to the shortcircuit current $I_k$. By giving suitable values to $d, L_n, L_p$ one can make $f_1$ come near to its maximum, 1. In Table I are calculated values for $f_1$ for various parameter values. The value for $f_2$ is given in brackets to simplify a comparison between $f_1$ and $f_2$.

Above the solid line in Table I, $f_1$ is at least 0.9, but falls rapidly under this line. The most suitable area is fixed by the following inequalities.

$$L_\lambda \geq d \qquad L_n \,;\, L_p \geq 10\, L_\lambda$$

$$L_\lambda < d \qquad L_n > 10\, d$$

One should not make d unnecessarily small, as otherwise the resistance in the p-layer will be large. $L_p$ is decided entirely by quality of the crystals. It follows that extremely good crystals are not essential.

## Measurements of $\tau_n$ and $\tau_p$.

In an alloyed p-n junction, indium in n-type germanium, the conductivity in the p-material is much greater than in the n-material.

Let $p_n$ denote the hole concentration in n-material with thermal equilibrium, and $\Delta p$ the induced concentration at the junction in the n-material. The total hole concentration at the junction will then be

$$p = p_n + \Delta p \tag{5}$$

In accordance with Shockley [5], we can write for the hole concentration at the junction

$$p = p_n\, e^{eV / kT} \tag{6}$$

where V is the voltage across the junction. From equation ( 5 ) and ( 6 ), one arrives at

Tabell 1.

| | | L = 100 d | L = 10 d | L = d | L = 0, 1 d | L = 0, 01 d |
|---|---|---|---|---|---|---|
| $L_p$ = 1000 d | $L_n/L_p$ = 10 | | | | | |
| | $L_n/L_p$ = 1 | 0, 910 ( 0, 910 ) | 0, 991 ( 0, 991 ) | 0, 998 ( 0, 998 ) | 0, 999 ( 1, 000 ) | 0, 999 ( 1, 000 ) |
| $L_p$ = 100 d | $L_n/L_p$ = 10 | 0, 505 ( 0, 505 ) | 0, 919 ( 0, 919 ) | 0, 994 ( 0, 994 ) | 0, 999 ( 1, 000 ) | 0, 999 ( 1, 000 ) |
| | $L_n/L_p$ = 1 | 0, 505 | 0, 919 ( 0, 919 ) | 0, 991 ( 0, 994 ) | 0, 991 ( 1, 000 ) | 0, 989 ( 1, 000 ) |
| $L_p$ = 10 d | $L_n/L_p$ = 10 | 0, 100 | 0, 548 ( 0, 548 ) | 0, 962 ( 0, 966 ) | 0, 991 ( 1, 000 ) | 0, 989 ( 1, 000 ) |
| | $L_n/L_p$ = 1 | 0, 100 ( 0, 100 ) | 0, 543 | 0, 930 ( 0, 981 ) | 0, 905 ( 0, 995 ) | 0, 896 ( 0, 995 ) |
| $L_p$ = d | $L_n/L_p$ = 10 | 0, 019 ( 0, 020 ) | 0, 173 | 0, 780 ( 0, 812 ) | 0, 905 ( 0, 995 ) | 0, 896 ( 0, 995 ) |
| | $L_n/L_p$ = 1 | 0, 016 ( 0, 017 ) | 0, 142 ( 0, 154 ) | 0, 551 | 0, 332 ( 0, 655 ) | 0, 365 ( 0, 648 ) |
| $L_p$ = 0, 1 d | $L_n/L_p$ = 10 | 0, 007 ( 0, 087 ) | 0, 069 ( 0, 081 ) | 0, 371 | 0, 332 ( 0, 655 ) | 0, 365 ( 0, 648 ) |
| | $L_n/L_p$ = 1 | | | | | |

$$V = \frac{kT}{e} \ln \left( 1 + \frac{\Delta p_o}{p_n} \right) \tag{7}$$

We can assume that the excited carrier concentration $\Delta p_o$ decays according to a single effective lifetime $\tau_e$, and so we arrive at

$$\Delta p = \Delta p_o \, e^{\frac{t}{\tau e}} \quad , \tag{8}$$

where $\Delta p_o$ is the excited carrier concentration at the moment of application of a current pulse in the direction of conduction. In such a case equation ( 8 ) can be substituted in equation ( 7 ). The constant ( $1 + \Delta p_o / p_n$ ) can now be expressed in terms of $V_o$ at time $t=O$, that is at the moment of rise and fall of the applied pulse, or

$$V_o = \frac{kT}{e} \ln \left( 1 + \frac{\Delta p_o}{p_n} \right) \tag{9}$$

if one now writes the voltage above the junction on the open circuit as a function of time, we have

$$V = \frac{kT}{e} \ln \left[ 1 + \left( e^{eVo/kT} - 1 \right) e^{-t/\tau e} \right] \tag{10}$$

As one can make $1/\tau_e$ very small, and $V_o \gg kT/e$ in practice, equation ( 10 ) can be simplified :

$$V \cong V_o - \frac{kT}{e} \frac{t}{\tau_e} \tag{11}$$

from which if is apparent that the variation in time of the current at the start

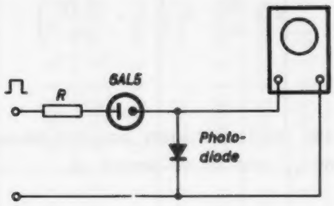



Fig. 2.a.

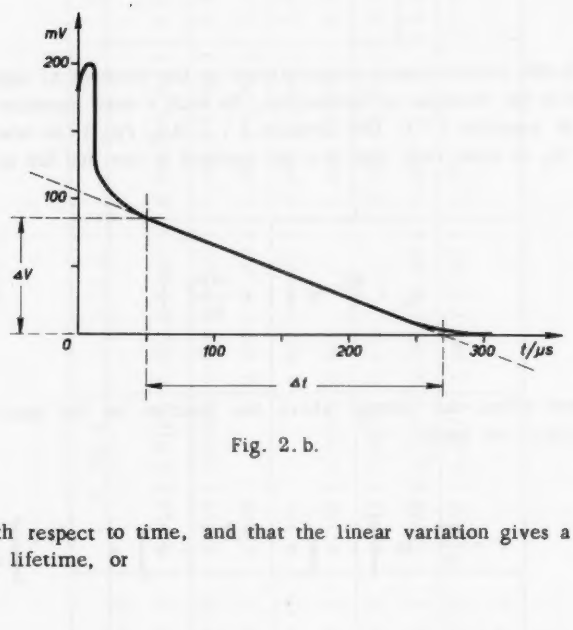



Fig. 2.b.

is linear with respect to time, and that the linear variation gives a measure of the effective lifetime, or

$$\tau_e = - \frac{t}{e/kT\Delta V} = - \frac{kT}{e} \times \frac{1}{\text{Linear voltagevariation}} \qquad (12)$$

Fig. 2. a. shows the experimental arrangement for measurement. A pulse is generated by a pulsegenerator, which is fed via a resistance R and a diode to the emitter on the semiconductor diode, from which the signal is connected to the y-amplifier of an oscilloscope.

During the time the pulse is applied to the diode, that is, the pulse duration, minority carriers are induced in the diode base. When the pulse begins to fall, the diode, 6AL5, disconnects the pulsegenerator from the measurement circuit, and one can examine the decay of the charge carrier on the oscilloscope. Fig. 2. b shows apparent decay. As shown above, $\tau_e$ can be arrived at from the linear part of this decay. $\tau_e$ thus consists of a surface and a volume component. With these measurements, the effective lifetime becomes the essential point, as we have not studied the separate components.

When making these measurements, it is important to use a pulse generator with a very rapid rise. These measurements were made with the following instruments.

1. -hp- pulse generator Type 212A
   pulse frequency 300 Hz
   pulse width 11 $\mu$s
   pulse amplitude 80 V = 100 %, 41 V = 50 %, 16 V = 16 %
2. Tektronix oscilloscope 535
   x-base calibrated to 50 $\mu$s/cm
   y-base -"- to 50 mV/cm

All the measurements given here have been checked. Measurements were made on six different germanium diodes.

Measured values

Table II

| Diode | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $\tau_e$ $\mu$s | 82 | 59 | 64 | 62 | 75 | 47 |
| $\tau_p$ $\mu$s | 22 | 31 | 12 | 17 | 10 | 22 |

## Diodes

Diodes were made of n-type gemanium with a resistance = 2, 9 $\Omega$cm. The length of the diodes is 3. 78 mm. Indium was used as an alloying substance.

Alloying was carried out with hydrogen as a protective gas with a rate of flow of 350 l/h. In this work, we applied a pressure to the indium pellet which was kept constant during the whole period of heating, but when the final temperature of 450°C was reached this pressure was increased. We thus produced a p-layer of 30-40$\mu$. Nickel was used as a contact material.

Etching of the complete diode was done electrolytically with a 10 % KOH-solution, using a current of 140 mA for 80 sec. The diode was rinsed with ionised water, subsequent rinsing being done with methanol, and final boiling in carbontetrachloride. The diode was dried in a vacuum oven for one hour at 120°C

## DETERMINATION OF THE QUANTUM EFFICIENCY OF THE PHOTO ELECTRIC EFFECT

### Theory

Equation ( 3 ) applies only to monocromatic radiation, and when one is forced to use polychromatic radiation, one should determine the wavelength dependence of I and integrate. The wavelength dependence of I can be determinded by means of an analysing crystal in a goniometer and a GM detector. From such a measurement one gets a function $f(\lambda)$ that gives the number of X-ray photons per unit area and unit time in the wave length interval $\lambda \cdots (\lambda + d\lambda)$ according to the equation

$$d N_{\lambda} = C_1 f(\lambda) d\lambda \qquad (13)$$

The photons in the wavelength interval provide the following contribution to the total radiation power

$$d I_0 = - \frac{hc}{\lambda} d N_{\lambda} = C_1 hc \frac{f(\lambda)}{\lambda} d = C_2 \frac{f(\lambda)}{\lambda} d\lambda \qquad (14)$$

where $hc/\lambda$ is the energy of one photon, and $c_2$ a constant which can be determined by measuring the radiation energy $I_0$ in r/s by the means of an ionisation chamber. We assume

$$1 \frac{r}{s} = \frac{5,2 \cdot 10^3}{(\mu/\varrho)} \left[ \frac{eV}{cm^2 \, s} \right] \qquad (15)$$

where ( $\mu$ / $\varrho$ ) is the mass absorbition coeffcient of air expressed in $cm^2/g$ . Combination with the previous equation ( 14 ) gives

$$\frac{d\ I_o}{\left[\frac{eV}{cm^2\,s}\right]} = \frac{5.2 \cdot 10^{13} \ \frac{I_o}{[r/s]}}{\int_\lambda (\mu/\varrho) \ \frac{f(\lambda)}{\lambda} d\lambda} \cdot \frac{f(\lambda)}{\lambda} \ d\lambda \qquad (16)$$

Through combining equations ( 3 ) and ( 16 ) one has

$$I_k = \frac{A e \eta}{E_g} \int_\lambda f_1 \ dI_o \qquad (17)$$

or by taking into consideration the above

$$I_k = \frac{A e \eta}{E} \ 5.2 \cdot 10^{13} \ I_o \frac{\int_\lambda f_1 \ \frac{f(\lambda)}{\lambda} d\lambda}{\int_\lambda \left(\frac{\mu}{\varrho}\right)_{air} \frac{f(\lambda)}{\lambda} d\lambda} \qquad (18)$$

and finally for the quantum efficiency

$$\eta = \frac{1}{5.2 \cdot 10^{13}} \ \frac{I_k \ E_g}{A e \ I_o} \cdot \frac{\int_\lambda \left(\frac{\mu}{\varrho}\right)_{air} \ \frac{f(\lambda)}{\lambda} d\lambda}{\int_\lambda \ f_1 \frac{f(\lambda)}{\lambda} \ d\lambda} \qquad (19)$$

Integration is here tedious, but the reliability of this method is completely comparable with that given by Tauc [2] .

## Experimental determination of $\eta$

The diode was enclosed in a brass box with a window so that A = 0, 132 $cm^2$. The window was covered wiht aluminium foil to exclude light.

The current generated through X-ray radiation was measured by means of a Leeds-Northup moving coil galvanometer. The sensitivity of the galvanometer was 29,4 $\mu$A/cm/m, and its resistance 16,4 $\Omega$. A variable resistance was connected in series with the galvanometer, so that the photoelement load could be varied. It was found that the current- voltage characteristic of the photoelement was linear, and the shortcircuit current could thus be arrived at easily from the point at which this straight line cut the voltage axis. See Fig 3.a and 3,b.

The X-ray radiation intensity was measured with a specially built ionisation chamber. The current of the ionisation chamber was measured with a Kin-Tel valve voltmeter model 203.

By measurement of the current-voltage characteristic of the ionisation chamber for various values of radiation, intensity and hardness it appeared that 300 V was a suitable value for all the intervals concerned.

The X-ray intensity was calculated from the formula

$$I_o = 3.00 \cdot 10^9 \frac{\varrho_o I_j}{A_j l_j \varrho} \quad [r/S] \qquad (20)$$

where

$I_j$ ionisation chamber current
$l_j$ length of collection electrode
$A$ ionisation chamber window area
$\varrho$ air density g/cm$^3$
$\varrho_o$ 0,00124 g/cm$^3$

In order to have the intensity expressed in eV/cm$^2$ s, the conversion factor in ( 15 ) was used.

According to equation ( 19 ), the efficiency is

$$\eta = \frac{I_o E_g}{A_o I_k f_1} \qquad (21)$$

During the measurements, the diode was irradiated with X-rays from an X-ray tube with copper anode. The tube voltage was varied between 10-30 kV. The radiation intensity distribution was examined first, by means of a calcite crystal in a goniometer, and it could be established that the intensity of the continuous radiation was one order of magnitude less than the Cu-K$_\alpha$radiation. Though the continuous radiation had a certain effect, which was shown by the fact that if one took the wavelength $\lambda$ = 1,54 Å, and calculated the efficiency $\eta$ by using

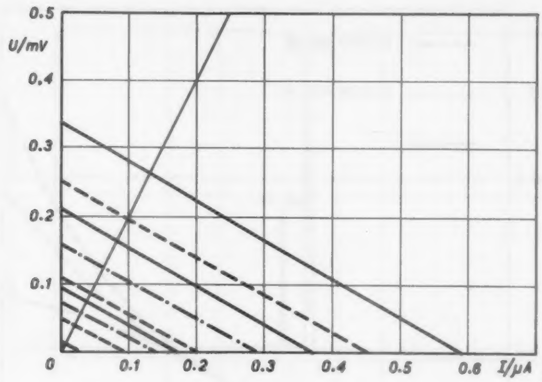



Fig. 3. a.

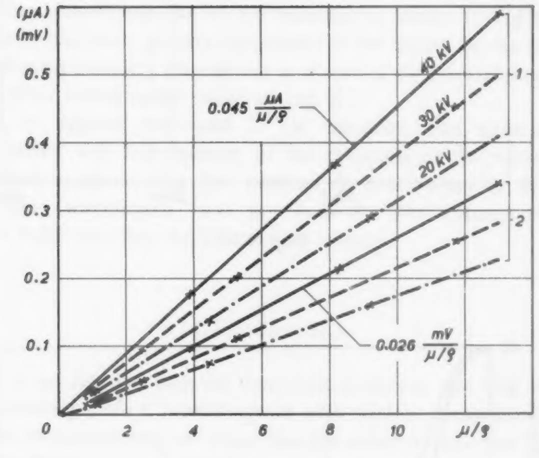
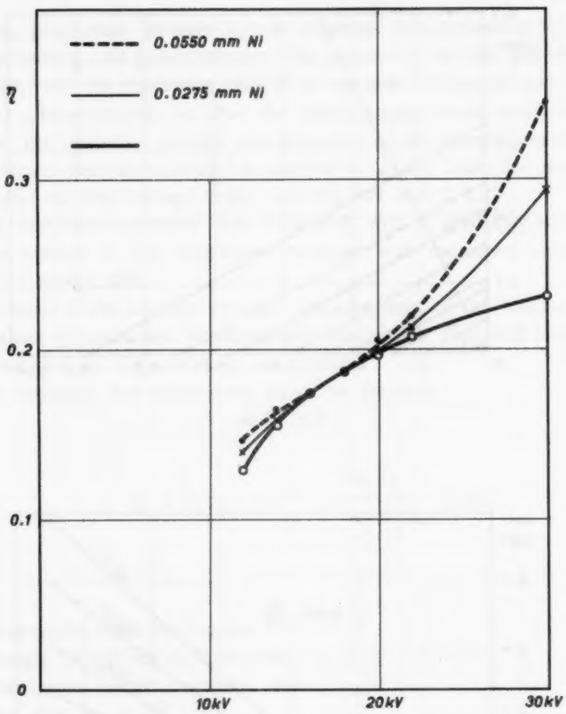



Fig. 3. b.

equation ( 21 ), then it was dependent on the voltage the X-ray tube.

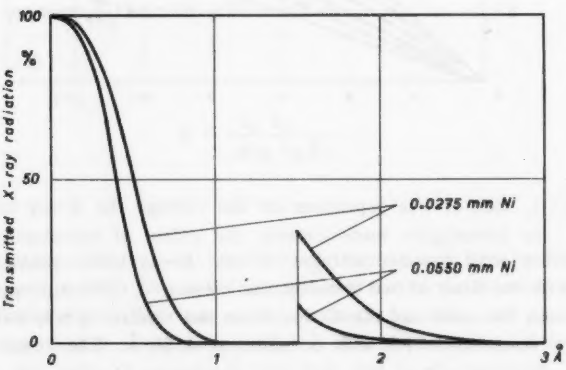
In order to investigate more closely the effect of continuous radiation and Cu-$K_\beta$ radiation with various voltages on the X-ray tube, measurements were made with a nickel filter of two different thicknesses, 0.0275 mm and 0.0550 mm, placed between the tube and the diode. From the results, $\eta$ was calculated again according to equation ( 21 ) with $\lambda$ taken as 1,54 Å. The result is shown in Fig. 4

The nickel filter affects the radiation distribution by emphasising the Cu-$K_\alpha$ line in comparison with the radiation at the other wavelengths, see Fig. 5. The



0.0550 mm Ni
0.0275 mm Ni
η
0.3
0.2
0.1
0
10kV
20kV
30kV


Fig. 4.



100
%
Transmitted X-ray radiation
50
0
0
1
2
3 Å
0.0275 mm Ni
0.0550 mm Ni


Fig. 5.

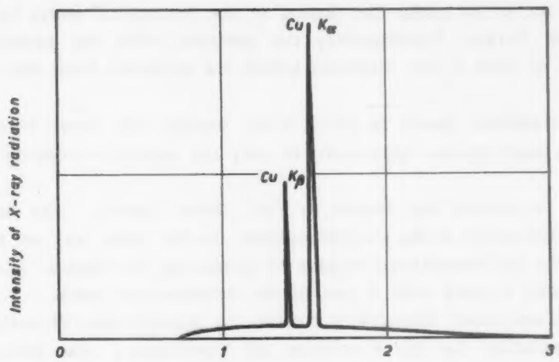



Fig. 6.

principal intensity distribution for 17 kV radiation is shown in Fig. 6. Continuous radiation intensity has been greatly exagerated in the figure for the sake of clarity. The filtered radiation intensity distribution is obtained by multiplying the curve of Fig. 5. by the filter transinission curve of Fig. 6.

From Fig. 4. it appears that with 17 kV radiation, the quantum efficiency calculated as above was independent of the thickness of the nickel filter. This can be interpreted to mean that the wavelength distribution at 17 kV was such that the "effective wavelength" was just 1.54 Å. The corresponding value of efficiency, $\eta$ = 0,18 can thus be assumed as correct.

## Conclusions

From Fig. 3. b we see that both the short circuit current and the photo-EMF rise linearly with intensity ( r/s ), which agrees with earlier measurements.

With lifetime measurements, we found that the effective lifetime $\tau_e$ had dropped from 150 $\mu$ s to 64 $\mu$ s. $\tau_e$ = 150 $\mu$ s was measured on the ready-treated diode material and consisted of $1/\tau_e = 1/\tau_\nu + 1/\tau_s$. We can thus assume that the voltage change which influences the material and on alloying, and which arises in particular from the p-n junction affects to a large extent the lifetime of the charge carrier in a diode.

We suggest that the low value of quantum efficiency is brought about as follows: The energy which goes to building an electron-hole pair is approximativly $E_g$, and as X-ray radiation energy is $h\nu$, there should be $h\nu / E_g$ electron-hole pairs per incident photon. As the X-rays also knock out electrons from the lower bands, we have also generated holes that will first after a certain time delay appear as holes in the edge of the valency band and thus assist the electrical conductivity. On the other hand, electrons appear more quickly in the conduction band. What

we do in fact is to make the doping of the p-material worse by radiating the element with X-rays. Consequently the potential over the junction diminishes.

A source of error is the electrons which are reflected from the surface of the crystal.

A drawn transistor should be much more suitable for these measurements, as one has thus much greater opportunity to vary the amount of doping when making the p-layer.

We wish to extend our thanks to Prof. Erkki Laurila, who helped us with advice and discussions as the work proceeded. In the same way we thank Dr Ernst Fröschle for the recomendations he gave for producing the diodes, and to Ing. Tapio Murto, who assisted with a part of the measurement work.

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